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EVALUATION OF TURBULENT AGGLOMERATION FOR FINE PARTICLE CONTROL

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16. ABSTRACT

The report gives results of an evaluation of the potential of turbulent agglomeration in enhancing fine particulate control. Available information on theoretical and experimental aspects of turbulent agglomeration indicates that this is not a very viable approach for improving fine particle control.

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SUMMARY

Fine particle control with conventional control devices will be much simplified if the particles can be made to form agglomerates. Agglomeration can be achieved as a result of different forces acting on the particles. This task was undertaken to evaluate the potential of turbulent agglomeration in fine particle control.

Both theoretical and limited experimental work indicate that the influence of turbulence on particle agglomeration is strongly dependent upon particle size, decreasing with decreasing particle size. Theoretical models suggest that turbulence does not significantly enhance the agglomeration constants for particles less than 0.2 μm in diameter, but can increase the agglomeration constant of 0.5-μm particles by about a factor of 10 and 1-μm particles by a factor of 100. In view of the fact that particles in the 0.1 to 0.5 μm size range are the most difficult to collect by conventional systems and one is most interested in achieving agglomeration in this size range, the preceding facts are discouraging. Fostering turbulence in a stream to enhance particle agglomeration with the intent of improving control of fine particles does not appear useful. If turbulence occurs naturally and does not act to the detriment of the main control system, then one could attempt to make use of the existing turbulence to achieve some agglomeration.

INTRODUCTION

Particle agglomeration can be enhanced by the turbulent motion of a flowing medium. The collisons of particles in turbulent flow are linked to the fact that particles are not fully entrained by turbulent eddies as a consequence of the significant differences in density between the medium and the aerosol particles. In addition, differences in inertial forces which are caused by differences in particle size also lead to collision between particles. These mechanisms are discussed in the next section. Experimental studies on turbulent agglomeration are also reviewed in a separate section.

THEORETICAL ASPECTS OF TURBULENT AGGLOMERATION

Turbulence can affect agglomeration by two different mechanisms. Suppose particles are suspended in a turbulent medium whose characteristic length scale of small eddies is larger than a characteristic particle size r_i . In the first case, since spatial nonhomogeneities are brought about by the turbulent flow, different velocities of neighboring particles must appear, causing collisions by a mechanism analogous to the mechanism of laminar shearing flow. In addition, each particle has a relative motion differing from that of the turbulent air because its inertia will not be the same as an equivalent mass of air. Since the inertia of particles depends on their size, the first mechanism can give rise to collision between both equally and unequally sized particles, while the second mechanism results only in encounters between unequally sized particles.

Theoretical studies on the agglomeration of aerosols in turbulent flow have been conducted by Levich,[1] East and Marshall,[2] Tunitsky,[3] Obukhov and Yaglom,[4] Beal,[5] and Saffman and Turner.[6] Levich[7] and Saffman and Turner both have made estimates of the agglomeration rate caused by the two mechanisms mentioned above. Their results apply to cases where the particle radii are smaller by an order of magnitude than the size of the smallest eddies. That is, these theories estimate the effect of turbulent motion on the scales determined largely by the viscosity of the fluid, and the dissipation rate of turbulent energy.

Although Levich used the concept of a turbulent diffusivity with Smoluchowski's method to obtain his results, Saffman and Turner applied a technique similar to kinetic theory, using probability theory to reach essentially the same conclusions.

Levich derived the following equations for the coagulation rate[7]

$$\psi = 32\pi r_p^3 \beta n_o \approx 25 \left(\frac{\epsilon}{\gamma}\right)^{1/2} r_p^3 n_o \qquad (1)$$

where β = coagulation constant,

γ = kinematic viscosity,

ϵ = rate of dissipation of turbulent energy per gram of medium $\left[\lambda_o \approx \left(\frac{\gamma^3}{\epsilon}\right)^{1/4} \right]$, and

λ_o = microscale of turbulence.

The ratio of the constants of turbulent and thermal agglomeration for this case is

$$A = K_1 \left(\frac{\epsilon}{\gamma}\right)^{1/2} \left(r_p^2 / D\right) \qquad (2)$$

where K_1 is a constant of the order 0.1 to 0.5. For particles 1 μm in radius $r_p^2 / D \approx 0.1$. Hence, it follows that for the agglomeration of such particles to be accelerated noticeably by turbulence $\sqrt{\epsilon/\gamma}$ must be about 100 and λ_o about 0.1 cm. This in turn requires a very high velocity. Under these conditions, the effect of turbulent agglomeration is negligible for particles of radius 0.1 μm while for particles of 10 μm it is very large.

Tunitsky assumed that agglomeration occurs in turbulent flow due to the relative fluctuation velocity at right angles to the lines of centers of the particles.[3] Using this approach Tunitsky develops an equation similar to Levich's.

$$\psi = 4 \left(\frac{\epsilon}{\gamma}\right)^{1/2} r_p^3 n_o \qquad (3)$$

Beal has extended Levich's analysis to include the effect of Brownian motion and has studied in more detail the case where the sink particle is larger than the turbulent microscale ($r_p > \lambda_o$) and has derived the following equation for the collision rate per unit area of sink particle.[5]

$$\phi = \frac{7}{3} B_1 \lambda_o^{2/3} \left(\frac{\epsilon}{\nu}\right)^{1/2} r_p^{1/3} n_o \qquad (4)$$

where B_1 = constant, ~ 1/4.

For this case the ratio of constants of turbulent and thermal agglomeration is

$$A = \frac{7}{12} \lambda_o^{2/3} \left(\frac{\epsilon}{\nu}\right)^{1/2} r_p^{4/3} \Big/ D \qquad (5)$$

Figures 1 and 2 present some of the results of Beal's theoretical calculations. As shown in Figure 1, the "exact" solution of the diffusion equation is asymptotic to the solutions based on either Brownian motion or turbulent diffusion alone and does not differ very much from a simple sum of these solutions. Figure 2 presents the normalized coagulation constant, K , as a function of particle diameter.

Beal's analysis has several limitations. Only the steady-state solution of the diffusion equation was obtained, only interactions among particles of equal size were considered, and all particles were assumed to stick together on impact. The last assumption is the most tenuous.

Inspection of Eqs. (1), (3), and (4) indicates that the key parameters influencing turbulent agglomeration are particle size (r_p) , particle concentration (n_o) , rate of dissipation of turbulent energy (ϵ) , and viscosity (ν) . Since the agglomeration rate varies directly with particle size, turbulent agglomeration will decrease in effectiveness as the particle size decreases--a discouraging result with regard to its utilization to collect fine particles. A decrease in the agglomeration rate with decrease in particle size could be compensated for by increasing the dissipation of energy or increasing the particle concentration. The former would require increasing the turbulence of the stream while the latter would undoubtedly involve seeding of the aerosol. However, in view of the fact that the agglomeration rate is a direct function of particle size, seeded particles may very well agglomerate with themselves and be of no use in promoting the agglomeration of fine particles. The extent to which the viscosity of the gas stream can be varied in an industrial application is limited, and gas viscosity is not a meaningful variable to use to modify the agglomeration rate.

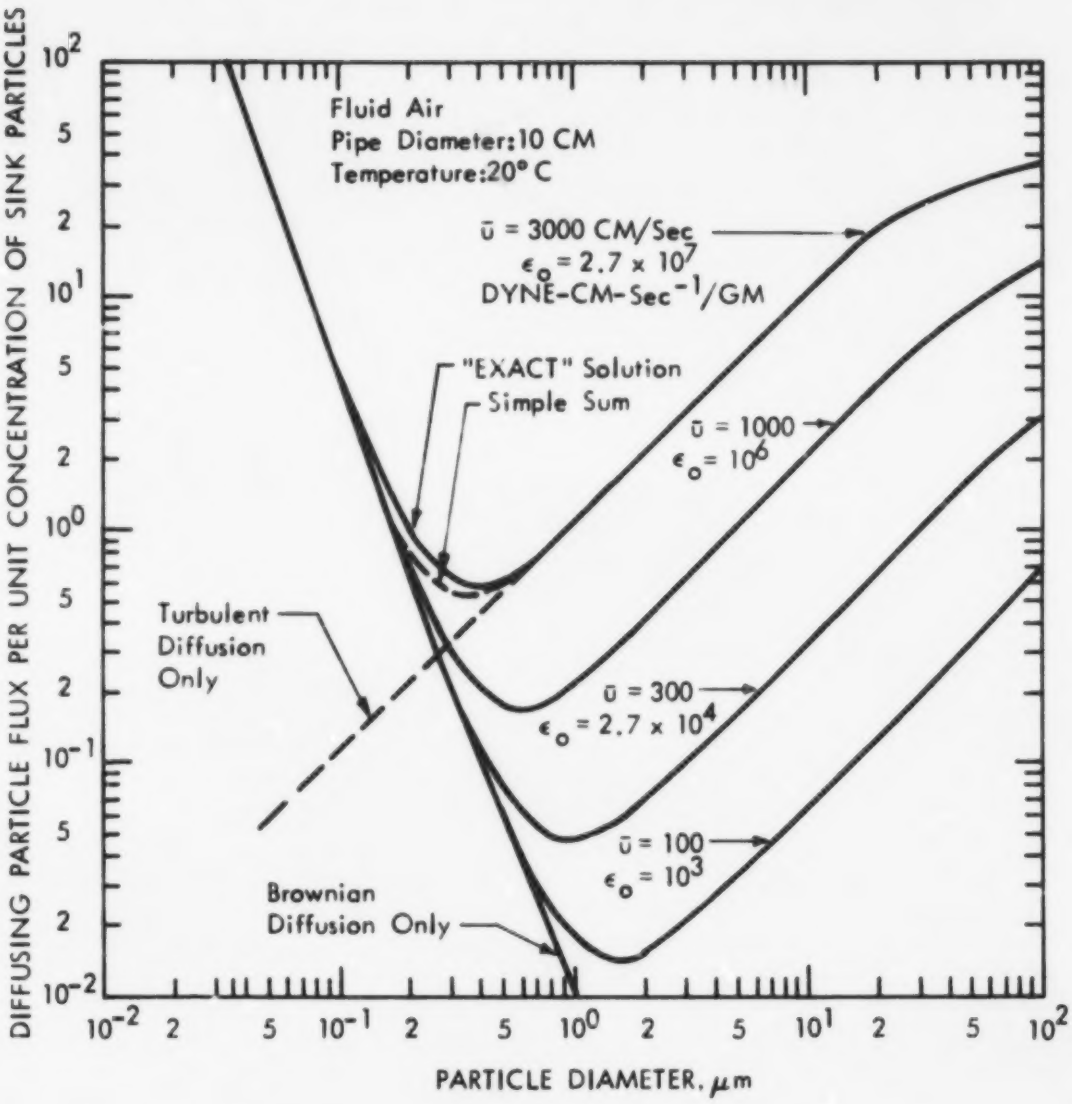

Figure 1. Particle agglomeration flux for various particle diameters and fluid velocities.

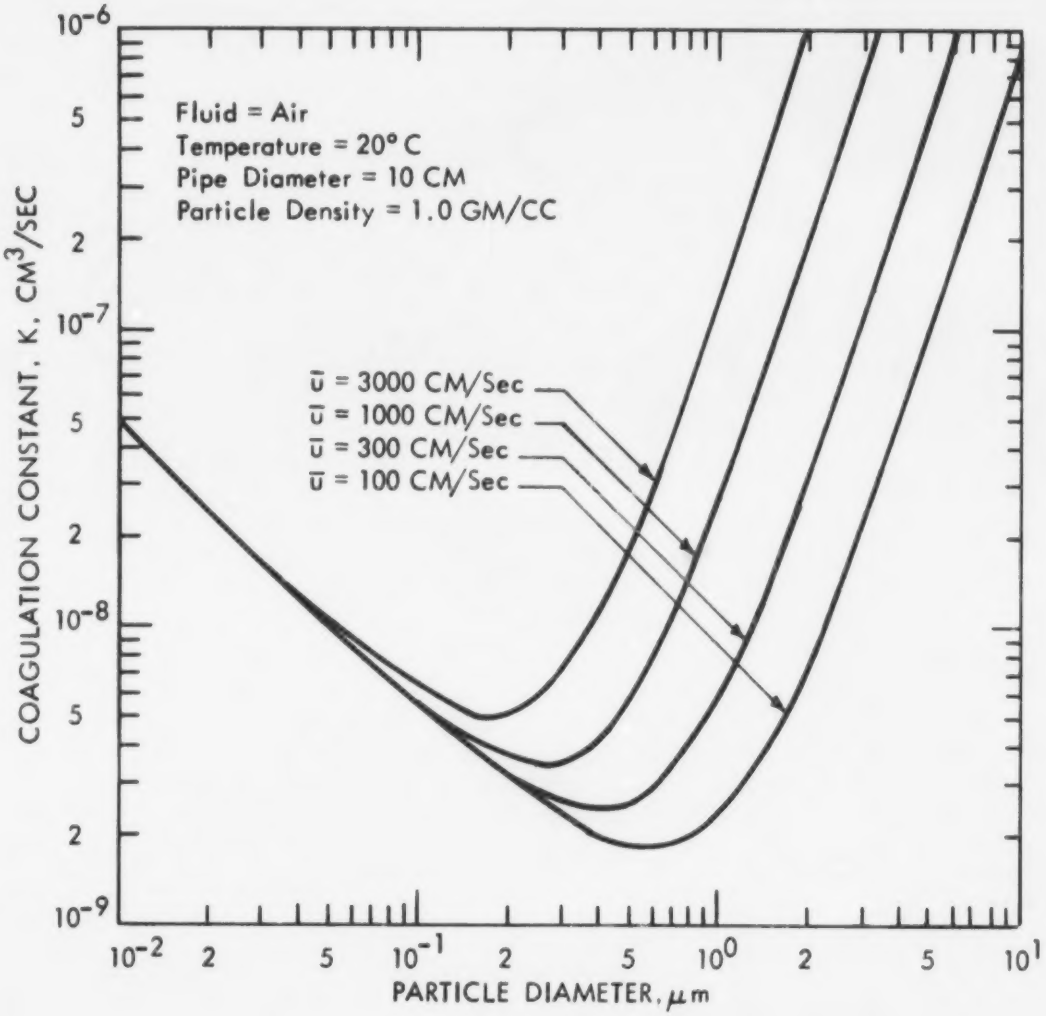

Figure 2. Coagulation constants for various particle diameters and fluid velocities.

Experimental work on turbulent agglomeration is meager and difficult to interpret. Pertinent work is discussed in the next section.

EXPERIMENTAL STUDIES OF TURBULENT AGGLOMERATION

Experimental study of the rate of agglomeration in the presence of turbulence is difficult because turbulence also accelerates the deposition of particles on walls. The rate of deposition increases with particle size so that the assessment of the course of agglomeration is complicated.

Langstroth and Gillespie made extensive experimental studies on agglomeration in strongly turbulent air.[8] They used a chamber with a volume of about 1 m^3 in which ammonium chloride smoke coagulated in static and in moving air with different degrees of turbulence. The air movement was produced by an oscillating agitator consisting of two perforated plates. Particle number and mass concentration were measured at intervals of 30 min over a period of 5.5 hr. Two constants were assumed in order to separate the effects of coagulation and of precipitation of the aerosol particles on the chamber walls. It is difficult to apply the results of these experiments to other chamber dimensions, particle sizes, and turbulent flows. The method used to stir up the air also introduces an uncertainty because the motion produced does not resemble any of the kinds of turbulence usually encountered in flow systems.

Experiments by Yoder and Silverman are the only results that appear to be subject to any rigorous analysis.[9] These investigators performed experiments to obtain data on the deposition and agglomeration of particles in turbulent air flow. In their experimental design, deposition and agglomeration were occurring simultaneously, and their basic problem was to separate the two effects. They did this by measuring both the total number concentration and the fraction of particles which had agglomerated at the inlet and outlet of their test section. By applying certain theoretical concepts, they could then infer the separate effects of both deposition and agglomeration from the measured parameters. They did not, however, make any direct observation of either phenomenon.

Beal utilized the data of Yoder and Silverman for a comparison with his theoretical predictions of particle agglomeration. Figure 3 presents this comparison. The agreement is reasonably good for the 0.8-μm particles, but poor for the 0.26-μm particles. No adequate explanation of the difference in magnitude between the observed and predicted values of the coagulation constant was offered by Beal. A general discussion of the difficulties encountered in the experimental determination of turbulent agglomeration coefficients is presented by Fuchs.[10]

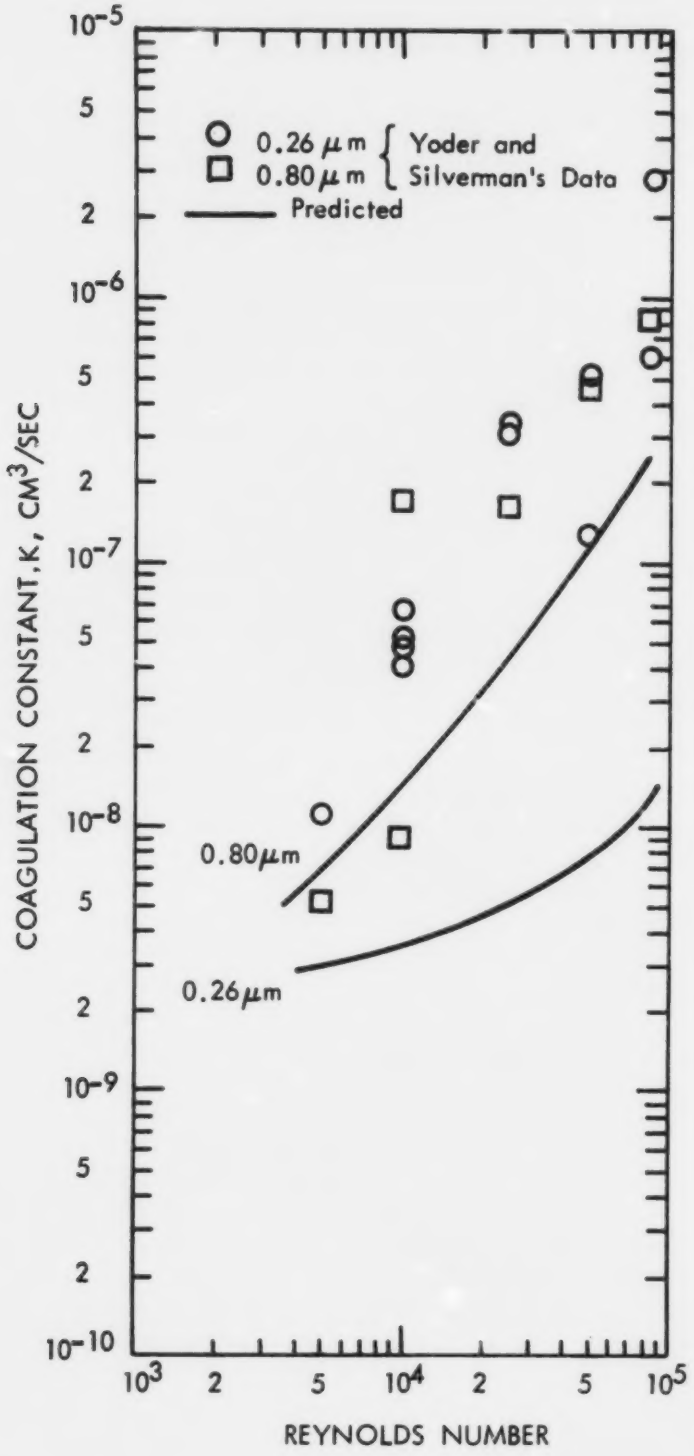

Figure 3. Comparison of theoretical predictions with Yoder and Silverman's agglomeration data.

CONCLUSIONS

Both theoretical and experimental work indicate that the influence of turbulence on particle agglomeration is strongly dependent upon particle size, decreasing with decreasing particle size. Theoretical models suggest that turbulence does not significantly enhance the coagulation constants for particles less than 0.2-μm in diameter, but can increase the coagulation constant of 0.5-μm particles by about a factor of 10 and 1-μm particles by a factor of 100 (see Figures 1 and 2). In view of the fact that particles in the 0.1 to 0.5 μm size range are the most difficult to collect by conventional systems and one is most interested in achieving agglomeration in this size range, the above observation is discouraging.

Considerations of energy expenditures required to achieve turbulent agglomeration also dampen enthusiasm for utilizing turbulent agglomeration in industrial applications. The energy expended to achieve the increases in the coagulation constant cited above is of the order of 10^7 dyne-cm-sec^{-1}/g or 0.001 hp/g. The preceding energy expenditure is equivalent to about 40 hp/1,000 ft^3 of gas. This is an extremely high energy consumption and, therefore, turbulent agglomeration is not very attractive if an external source is required to provide the turbulence. Even if energy levels of that magnitude were expended, it would take approximately 1 min to increase the size of a 0.5-μm particle to 2 to 3 μm.

The preceding discussion indicates that fostering turbulence in a stream to enhance particle agglomeration is not very useful. If turbulence occurs naturally and does not act to the detriment of the main control system (e.g., turbulence often degrades ESP performance); then one could attempt to make use of the existing turbulence to achieve some agglomeration.

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